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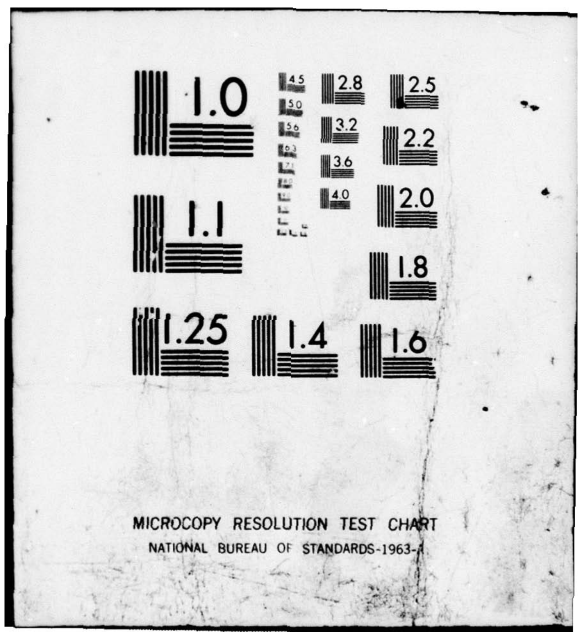
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MELBOURNE, VICTORIA

Structures Technical Memorandum 278

REPORT ON VISIT TO U.S.A. AND CANADA,
MAY/JUNE 1978, RELATING TO THE FATIGUE OF MATERIALS

J.M. FINNEY

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SUMMARY

In May/June 1978 the author visited the U.S. Air Force Materials Laboratory to arrange the joint final report for the 'US/Australia Collaborative Research Project on Corrosion Fatigue in D6AC Steel Joints'. This report details those discussions and other discussions on the fatigue of materials held during associated technical visits. In addition, a brief report is given of the proceedings of a Symposium on Fatigue Mechanisms also attended.

POSTAL ADDRESS: Chief Superintendent, Aeronautical Research Laboratories, Box 4331, P.O., Melbourne, Victoria, 3001, Australia.

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1. PURPOSES OF VISIT

(i) The primary purpose of the visit was, as the Australian Project Officer, to meet with the Project Manager, Mr. C.L. Harmsworth of the US Air Force Materials Laboratory (AFML), to arrange the joint final report for the "US/Australia Collaborative Research Project on Corrosion Fatigue in D6AC Steel Joints".

(ii) Secondary purposes were to attend a Symposium on Fatigue Mechanisms, and to visit four research centres in the U.S.A. and Canada studying aspects of fatigue and cumulative damage which are relevant to ARL aims and programs on fatigue life estimation.

2. PROGRAM

The author departed Australia on 19 May 1978, and returned on 13 June 1978, and during this period the program was as follows:

Monday 22 May to Wednesday 24 May	:	Symposium on Fatigue Mechanisms at Kansas City, Mo.
Friday 26 May to Wednesday 31 May	:	Wright-Patterson Air Force Base, Dayton, Ohio. Main visit to Mr. C.L. Harmsworth, Air Force Materials Laboratory (AFML) and other visits to Dr. W.H. Reimann (AFML) and Mr. J.M. Potter, Air Force Flight Dynamics Laboratory.
Thursday 1 June	:	Australian Embassy, Washington, D.C.
Friday 2 June	:	National Bureau of Standards, Gaithersburg, Md.
Monday 5 June	:	University of Pennsylvania, Philadelphia, Pa.
Wednesday 7 June	:	Lehigh University, Bethlehem, Pa.
Friday 9 June	:	University of Waterloo, Waterloo, Ontario, Canada.

3. <u>DISCUSSIONS WITH MR. C.L. HARMSWORTH, AIR FORCE MATERIALS LABORATORY (AFML), WRIGHT-PATTERSON AIR FORCE BASE (W-PAFB) DAYTON, OHIO, MAY 26-31, 1978</u>

The collaborative research project carried out between the AFML and ARL is entitled "US/Australia Collaborative Research Project on Corrosion Fatigue in D6AC Steel Joints". Briefly, the manufacture of D6AC steel lap-joint specimens bolted together with Taper-Lok interference fit fasteners, was arranged by AFML and some were forwarded to ARL for test. These specimens simulated the construction of the F-111 wing carry through. AFML investigated the effects of humidity and temperature, and changes in sealant and re-work procedures, on the fatigue life of the specimens, and ARL investigated the effects of bolt hole contaminants (water and hydrochloric acid) on fatigue life. (The project was initiated by the ARL finding of contaminants in such holes).

Identical loading conditions were employed by both countries and tests were made under both constant amplitude and spectrum loading. The results confirmed the adequacy of the F-111 design and the usefulness of current F-111 re-work procedures in the absence of bolt hole contaminants. Water, as a bolt hole contaminant, did not reduce fatigue life but a drastic reduction in life was obtained under spectrum loading when hydrochloric acid was deliberately introduced into the bolt holes, although the acid did not reduce life under constant amplitude loading.

Annexe B, item 4 of the Project Arrangement between the two countries, signed in 1973, states:

> "Immediately following the completion of the testing effort, the AARL project officer will visit the AFML to discuss the use of appropriate analysis and presentation techniques for the joint final report. Following this visit each party will prepare and exchange drafts of their respective portions of a final report. The AFML will incorporate both drafts into a integrated joint report which will be subject to AARL review before final publication by AFML".

Before the visit AFML had prepared a draft containing a description of their tests and results and had forwarded a copy to ARL. Similarly, a draft report of the ARL contribution, covering both the test results and their analysis, had been prepared and sent to AFML on 11 May 1978.

The visit to AFML thus centred on arranging a joint report layout, discussing various technical aspects, and agreeing on suitable analyses and presentations. The agreements reached with Harmsworth were as follows:

(a) One report would be produced consolidating the separate parts of the project. The layout of the report is to be:

Introduction
Specimen manufacture
Interlaboratory test procedures
Effects of external environment (i.e. AFML results)
Effects of contaminants in bolt holes (i.e. ARL results)
Conclusions, etc.

(b) The complete substance of the ARL draft contribution will be included.

(c) The AFML results will be statistically analysed and suitable modifications made to the AFML draft content.

(d) The authorship of the joint report will be C.L. Harmsworth, D.S. Kemsley (former Australian Project Officer), J.M. Finney, with acknowledgements given to other AFML and ARL contributors in a Foreword.

(e) The report (to be produced by AFML in their format) will contain both AFML and ARL names, addresses, task numbers and report numbers.

(f) Although the Project Arrangement between the countries specified the production of 100 copies of a final report by AFML, and 50 of these copies to be sent to ARL, Harmsworth is agreeable, and he believes the AFML will support the move, to produce approximately 250 copies for ARL for our normal report distribution. AFML would make the distribution within the US on behalf of ARL, thus forwarding about 200 copies to ARL. These copies will be produced without charge.

A sustantial part of the text of the report was agreed upon during the visit; the stages now to follow are:

- the ARL results section of the report to be re-arranged to conform with the combined layout, and copies sent to AFML.

- AFML to adequately analyse their results and re-write their discussion and conclusions (some of this was done during the visit).
- AFML to send a typed draft of the combined report to ARL for final vetting.
- AFML to publish the report.

Despite the ARL finding that the spectrum load fatigue life of the joint specimens is drastically reduced by contaminating the bolt holes with concentrated hydrochloric acid, Harmsworth did not want to extend the project to investigate this aspect further. He believed that the U.S. F-111's were unlikely to be so contaminated.

4. OTHER DISCUSSIONS AT WRIGHT-PATTERSON AIR FORCE BASE

During the time at W-PAFB the opportunity was taken to visit two other areas working on fatigue.

4.1 Discussion with Mr. J.M. Potter, Fatigue and Fracture Group, Structures Division, Air Force Flight Dynamics Laboratory (AFFDL), W-PAFB, May 30, 1978.

Potter described a number of projects relating to the practical assembly-line production of aircraft and to the prediction of fatigue life.

(a) Examinations of laboratory fatigue failures in specimens with drilled holes did not reveal any correlation between the location of flaws as determined by NDI and the sites of fatigue fracture. This led to the attempt to establish "equivalent" initial flaw size distributions by extrapolating backwards from measurements of larger flaws (cracks). The aim is then to use fracture mechanics with the equivalent initial flaw sizes to predict growth rates under any load sequence.

With this background a study was made of the effect of hole quality on the initiation of fatigue cracks in drilled and drilled plus reamed specimens. 7475 aluminium alloy (the F-16 and C5A wing re-work alloy) was used and specimens were tested under flight-by-flight sequences representing either a fighter or bomber history.

There was a considerable difference in the flaw size probability distributions of the two machining procedures and this led to a detailed study of the machining techniques. It was found that the likelihood of larger flaw sizes with drilled samples arose from the long axial scratches on the hole surface as the drill was retracted. By rotating the drill during retraction there was a 10-fold decrease in initial equivalent flaw size and a 10-fold increase in fatigue life. As a result, the production line of the F-16 is being re-built, there is less emphasis on inspection, and the scatter in hole sizes is decreased from 0.002-0.003 inch to 0.001 inch (standard deviation).

(b) A number of different fastener systems have been developed by different manufacturers who claim that their product enhances the fatigue life of structural components when compared with the

common driven rivet or straight shank bolt in clearance holes. The U.S. Air Force found it difficult to choose among the claims of the manufacturers and a study was initiated to contrast the fatigue performance of 34 fastener systems.

Low-Load transfer specimen blanks of 7075-T6 aluminium alloy were prepared and sent to each manufacturer who installed the fasteners. All fatigue tests were made at AFFDL using the one machine, and a single level of constant amplitude loading. A report on this work is available* and the second phase of flight-by-flight testing is proceeding. From the constant amplitude results it appears that the fastener installation process (taper interference or driven/upset system) as well as the fastener geometry has a major effect on resultant fatigue life.

(c) Residual stresses are frequently introduced into a metal to improve fatigue performance and two recent examinations** were described in which such stresses were measured using the x-ray technique.

Residual stresses were measured around fastener holes in 1045 steel which were permanently expanded by different amounts. The shape of the hoop and radial stress profiles accords with current analytical results, but the zone of compression is wider and the maximum radial stress is more compressive than analysis predicts.

One problem in using residual compressive stresses to offset tensile fatigue stresses is the uncertainty in the permanancy of the residual stresses. Residual stress measurements were made on shot peened 7075-T6 aluminium alloy specimens after fatigue cycling and after thermal exposure. There was no change in the magnitude of the residual stresses after fatigue, but exposure to temperatures above 200°F significantly reduced the magnitude.

(d) Life prediction methods and cycle counting algorithms are also being investigated. In previous prediction methods used by AFFDL there appears to have been too much emphasis placed upon the phenomenon of crack growth retardation and a study is being undertaken to determine the important parameters in load spectra. Using flight-by-flight testing, the mission mix

* "Evaluation of fatigue rated fastener systems: Constant amplitude fatigue test results". J.M. Potter, R.P. Stewart, and F.D. Adams. AFFDL-TM-77-75-FBE, Nov. 1977.

** "Stress measurements on cold-worked fastener holes". G. Dietrich and J.M. Potter. Advances in X-ray analysis, Vol. 20, 1977. pp. 321-328.

"The effect of temperature and load cycling on the relaxation of residual stresses". J.M. Potter and R.A. Millard. Advances in X-ray Analysis, Vol. 20, 1977, pp. 309-319.

and the level of the highest load appear important, but the inclusion of compressive loads is not - almost the same life is obtained if the compressive loads are omitted.

Various cycle counting algorithms have been compared* and the range pair method, although essentially equivalent to the rain flow method, appears to offer some advantages in application.

4.2 Discussion with Dr. W.H. Reimann, Fatigue Group, AFML, W-PAFB, May 30, 1978.

The discussion with Reimann centred on low-cycle fatigue of engines, an area in which ARL is commencing involvement. A major problem had arisen in determining the safe life of components in the TF30 engine, and particularly that of the nickel-base superalloy compressor discs. Pratt and Whitney Aircraft (PWA) had originally determined a life of 6500 cycles but subsequently discovered a mistake in their stress analysis and a revised life of 2800 cycles was promulgated, despite the fact that at that stage the average operational life was 3500 cycles. Using this minimum life approach the U.S. project on annual expenditure of $US 50-80M on such discs by the mid 1980's.

Reimann is managing a large Engine Life Prediction program placed by the USAF on NASA (Lewis) but he is unhappy with their using the strain range partitioning approach for determining the safe life of compressor discs. The AFML are therefore conducting an independent assessment, i.e. independent of PWA and NASA, of life estimation procedures suitable for compressor discs.

In conjunction with the Aero Propulsion Lab. at W-PAFB independent life estimates are being made based on total-strain-controlled material test data. These estimates are being confirmed by hot spin pit tests and an accelerated mission test (AMT) on the complete engine.

There is a need for developing inexpensive life estimation procedures. One spin pit test at room temperature costs approximately $US 25,000; at test temperature the cost is about $US 100,000; and the AMT costs about $US 10,000 per hour, with the expected total being $US 600,000, $US 400,000 of which is for fuel.

The general procedure used by the AFML for estimating low cycle fatigue life is identical with that recently proposed by ARL. Reimann would be very interested in the results of any ARL work on

* "A comparison of two cycle counting algorithms". J.M. Potter. Trans. SAE, 1976, pp. 300-307.

other components in the TF30 engine, he suggested collaboration, and he is willing to assist ARL with details of life estimation techniques and acquisition of material.

The detailed stress analysis of discs was done by the Aero. Propulsion Lab. They defined the mission profile of the engine, did a structural analysis of the whole rotor, and a detailed analysis of the discs, defining the temperature and stress histories. This work involved the use of various models and computer programs and Reimann believes that this structural analysis information (and programs) could be made available to ARL without cost.

An important aspect of estimating low cycle fatigue life using materials test information is to obtain this information on virgin material manufactured identically with the service component. For compressor discs it is possible to procure "pancakes" from PWA: these are similar to a disc without machining. A pancake of superalloy, about 40 cm diameter and 2.5 cm thick costs about $US 4000.

5. BRIEF REPORT ON SYMPOSIUM ON FATIGUE MECHANISMS HELD IN KANSAS CITY, MO, MAY 22-24, 1978

This symposium was jointly sponsored by the American Society for Testing and Materials, the U.S. National Bureau of Standards, and the U.S. National Science Foundation. The proceedings of the symposium are to be published in an ASTM Special Technical Publication, hopefully within six months of the meeting. Twenty-eight papers were presented, as well as official discussions, over the six sessions. These sessions are briefly summarised below.

I. Quantitative microscopy and direct observations at dislocation level.

Quantitative microscopy, covering the subject of stereology, has had very little impact on fatigue studies although it has great potential in this area. One of the problems is that mechanical effects such as fracture are associated with geometrical extrema. Techniques such as weak-beam transmission electron microscopy are proving useful in quantitative studies and there are good hopes for the scanning electron microscope technique of observation as the resolution is improved to below 100 Å.

There are advances in the understanding of dislocation behaviour in fatigue, but mainly for specific metal systems. One paper dealt with a dislocation model of slip processes in the h.c.p. material Ti-6Al-4V and related the model to the observation of subsurface fatigue crack initiation. The soundness of ideas based on such a huge jump in scale is doubted.

The understanding of how persistent slip bands (PSB's) form in both fcc and bcc metals is gradually being revealed. It is established that they begin to form at the end of cyclic hardening but the basic dislocation mechanism of their formation is still speculative. Fcc metals always accommodate cyclic strain by PSB formation whereas such accommodation in bcc metals frequently occurs by cell formation, the cells decreasing in size with accumulated strain. Under certain conditions however (low strain rate and elevated temperature), PSB's are formed in bcc metals and they have exactly the same features as in fcc metals.

Dislocation structures around the tips of fatigue cracks in iron have been studied by Japanese workers using the worlds only 2MV transmission electron microscope. The detailed dislocation configuration around and just ahead of the crack tip depends upon the crack growth rate.

II Direct observations from slip bands to nucleation of microcracks.

It is generally agreed that fatigue cracks form at the surface of a metal by the formation of a notch/peak topography due to localised slip, and that cracks frequently grow by a process of plastic blunting at the crack tip.

In liquid metal environments, and possibly in some aqueous solutions, chemisorption is thought to facilitate dislocation nucleation at the crack tip leading to increased growth rates. Some factors affecting the stage I mode of crack growth have now been elucidated and it has been demonstrated that a PSB runs ahead of a stage I crack. Temperature, environment, alloy additions, and test frequency all influence the growth rate and the mode, and it is claimed that their influences result from their effect on the PSB running ahead of the crack.

Crack propagation tests have been made in the scanning electron microscope and have confirmed the slipping-off mechanism of stage I growth. The grain size of a low-carbon steel is shown to markedly influence the threshold stress intensity for stage I growth.

Electron chanelling is being used to study the plastic zone size and shape and the strain distribution ahead of a fatigue crack. It was shown on 6061 aluminium alloy that the plastic zone has the same size on the surface as in the interior of the metal, a result not previously thought to be so. The plastic zone shape changes through the thickness however.

III Direct observation of ductile and brittle striations, voids and microcracks.

There are numerous fatigue fracture modes. In A/B titanium and Fe-base alloys there are at least ten alternative fatigue fracture processes compared to the more common striation process. The modes depend upon material microstructure, test temperature, frequency and environment.

Non-propagating cracks are frequently observed at low cyclic stresses and in one case at least, a microstructure of ferrite and martensite, the threshold stress intensity for crack growth is that needed to propagate the cracks in the ferrite matrix into the second-phase martensite.

In copper and Fe 3% Si it was shown how extrusion-intrusion pairs can form as a consequence of stage I cracks. Stage II growth was demonstrated as an alternate-slip sliding-off process, and re-welding appears to occur during compression in stages I and II. Under certain testing conditions (slow rate of plastic strain) stable cleavage is observed in cycling Fe 3% Si.

It is clear that microstructure and environment affect crack growth rate (da/dN) in certain growth rate regimes, but an attempt to relate the da/dN behaviour to slip behaviour in the microstructure was not very convincing. Similarly, an attempt was made to predict crack growth from slip line observations using fracture mechanics, an approach severely criticised since there is a perceptual difficulty associated with specifying crack initiation in terms of a crack size.

IV Direct observation of microstructural damage due to fatigue with time dependency.

Two papers discussed fatigue of polymers, using the techniques and presentations developed for metal fatigue. In ductile polymers all micromechanistic deformation phenomena result in cyclic softening; cyclic hardening never occurs irrespective of temperature and strain rate. Changes in the magnitudes of these latter variables simply alters the degree of cyclic softening.

As with metals, crack growth rates in polymers are strongly dependent on the prevailing stress intensity factor (ΔK) at the advancing crack front, but there are differences in that striation spacings in polymers are found to vary with ΔK to the power of 4 to 20. Furthermore, discontinuous crack growth occurs in polymers and fracture modes may occur which are not observed in metals. The discontinuous growth process in single phase amorphous polymers is associated with the failure of a single craze ahead of the crack tip.

Several papers dealt with elevated temperature fatigue mechanisms. It is clear that, over a variety of alloy systems, the fatigue fracture mode depends on temperature, microstructure, and test frequency. The environment also affects the initiation and propagation of fatigue cracks at elevated temperature. Additionally, a surprising result is the observation that fracture modes and fatigue life depend upon the relative strain rates in the tension and compression parts of the fatigue cycle. For a constant cyclic period the fatigue life of copper at elevated temperature decreased by an order of magnitude as the tensile-going strain rate was reduced by two orders of magnitude. Such an effect appears related to the strain rate sensitivity of grain boundary sliding at elevated temperature.

V Quantitative microscopy and mathematical modelling for basic mechanisms of fatigue.

Modelling of fatigue behaviour was examined by a number of approaches.

(i) Stereological methods have been applied to characterize various aspects of metal microstructures which are thought to be important in the micro fatigue process. It is thus possible to characterize elongated structures, lamellar systems, gradients and locational features of particles with respect to the fatigue process.

(ii) Improvements in predictions using fracture mechanics can be expected when the assumption of linear elastic behaviour at the crack tip is replaced by an explicit treatment of plastic behaviour. This is especially significant in fatigue where the plastic deformation at a crack tip created during previous load cycles significantly affects the subsequent growth rate. It is perplexing that observed constant amplitude fatigue crack growth rates appear insensitive to yield stress, a parameter which is necessarily involved in any mathematical model of crack tip plasticity.

(iii) The application of micro-creep information to the study of time-dependent fatigue has been examined leading to a theory of fatigue crack initiation.

(iv) The complexity of the microstructure of metals and the emergence of quantitative microscopy has created the need to introduce statistical tools to the fundamental aspects of fatigue research. The statistical concept of stress in a medium with imperfections is introduced to permit modelling - this is a departure from the conventional continuum viewpoint.

VI Fatigue of composite materials and environment-assisted fatigue.

Fatigue mechanisms in composite materials, including eutectic composites, are quite numerous compared with mechanisms operative in conventional metals. This is evident by the various and complex failure modes shown by composites under fatigue cycling, such as combinations of matrix, fibre, and interfacial cracks and debonds. Fatigue mechanisms in composites depend upon a number of parameters including the material system, stacking sequence of plies, geometry, stress state, and environment. This variety leads to difficulties in currently predicting fatigue life for composite materials.

A review of corrosion fatigue studies over the past decade was presented and one method of forming a stage I fatigue crack in an aggressive environment was described. This method included the kinetics of pitting corrosion in consonance with alternating strain.

6. OTHER VISITS

6.1 Visit to National Bureau of Standards, Gaithersburg, Md., June 2, 1978.

Main purpose of visit.

To discuss statistical aspects of fatigue and basic fatigue mechanisms studies.

Persons contacted:

Dr. A.W. Ruff, Head, Metals Science and Standards Division.
Dr. R.J. Fields, same Division.
Dr. B. Christ and Dr. J. Smith, Fracture and Deformation Division.
Dr. A. Fraker, Polymers Division.

Unfortunately two key people working on statistical aspects of basic fatigue behaviour and on fundamental fatigue damage studies were absent. Discussions were held on the application of fatigue analysis to practical problems. These included the following:

(i) A catastrophic failure had occurred in a thick-walled pressure vessel mounted on a road trailer used for hauling methane, hydrogen, and natural gas. The quenched and tempered steel microstructure was banded and cracks tended to run along the hard bands. Metallurgical examinations and materials tests indicated the following failure sequence: initial cracking by

stress corrosion or hydrogen embrittlement, crack propagation by fatigue due to road loads, ductile fracture at a critical crack length. As the vessel failed, when being filled, at a pressure of about 2000 p.s.i., and the design rupture pressure is 4500 p.s.i., recommendations will be made about redesign and quality control.

(ii) As the Bureau is responsible for developing standards and test procedures, some work is proceeding on:

(a) stress corrosion tests at elevated temperature - the aim being to establish valid K_{ISCC} and fracture toughness tests suitable for application in reactor vessel design,

(b) fracture mechanics tests suitable for fatigue life prediction, taking into account plasticity effects.

(iii) Ti-6Al-4V alloy is being examined for its use in hip implants. Such a prosthetic device is subject to about 3 million load cycles per year and it operates in a corrosive environment. Work is initially proceeding on optimising the microstructure of the alloy by heat treatment for fatigue resistance under simulated physiological corrosive solutions.

6.2 <u>Visit to University of Pennsylvania, Philadelphia, Pa., June 5, 1978</u>.

Main purpose of visit.

To discuss studies of the cyclic stress/strain behaviour of metals and basic studies on cumulative damage.

Persons contacted:

Prof. C. Laird, Chairman, Department of Metallurgy and Materials Science.
Dr. S. Bhat and Dr. Z. Hashin of the same Department.

A number of studies are being undertaken on the response of various microstructures to fatigue, basic aspects of hysteresis loops and dislocation behaviour in P.S.B.'s, models of crack propagation, and cumulative damage.

(a) Behaviour of hardened microstructures under fatigue cycling.

The aim of most of these studies is to infer the basic mechanisims of dislocation/precipitate interaction under fatigue stressing by measurement of the cyclic stress/strain response of the metal and thin foil observation of microstructures. One

investigation* dealt specifically with the postulate that cyclic softening in a precipitation hardened structure occurs by loss of the ordering component of hardening as precipitates are traversed by dislocations. An alternative postulate is that simple shearing of precipitates ultimately allows easier passage of dislocations on the shear plane. Al-15%Ag heat treated to contain Gp zones did not cyclically soften under constant plastic strain fatigue. As these precipitates are not ordered, and yet would be cut by the passage of fatigue dislocations, the conclusion is that the results support the disordering hypothesis. The behaviour of this alloy raises complications however in that the cyclic strain induces the nucleation and growth of γ precipitates and this process gives rise to large degrees of cyclic hardening.

Another investigation concerns the influence of high temperature cyclic deformation on the microstructure of nickel, TD-nickel, and Al-4%Cu aged to contain either Θ' or Θ'' precipitates. For nickel, the cyclic flow stress decreases linearly with increasing temperature up to about 2/3 m.p. and then drops sharply. This rapid decrease appears associated with rapid dislocation rearrangement leading to cell coarsening. On the other hand TD-nickel shows little change in cyclic flow stress and microstructure up to 2/3 m.p.

In Al-4%Cu the plate-like Θ' particles are effective in increasing the cyclic flow stress at room temperature and they help to retain cyclic strength at elevated temperatures. However, with continued cyclic plastic strain the Θ' particles become plastically twisted, eventually slicing in two, and transforming to Θ. In the Θ'' microstructure cyclic hardening is followed by softening at all temperatures studied; the softening is thought to occur as a result of the destruction of order.

(b) Fatigue of pseudoelastic materials.

Little is known of the fatigue behaviour of pseudoelastic materials although theoretically they should have outstanding fatigue properties. An investigation has been made** of a Cu-14.5Al-3Ni alloy to determine its cyclic behaviour and fatigue life. Because of brittleness of the alloy tests were made in pulsating compression. The alloy behaved like a conventional

* "The cyclic stress-strain response of precipitation hardened Al-15wt.%Ag alloy". C. Laird, V.J. Langelo, M. Hollrah, N.C. Yang and R. de la Veaux. Mat. Sci. Eng., Vol. 32, 1978, pp. 137-160.

** The cyclic stress-strain response of polycrystalline, pseudoelastic Cu-14.5wt Pct Al-3wt Pct Ni alloy. N.Y.C. Yang, C. Laird and D.P. Pope. Met. Trans A, Vol. 8A, June 1977, pp. 955-962.

metal, giving superior fatigue life only at low cyclic strains. Cyclic hardening occurred, and fatigue fracture nucleated at grain boundaries in and near which stress-induced-martensite is produced. The material also obeys the Coffin-Manson law of fatigue life.

(c) Studies of hysteresis loops and persistent slip bands.

Two separate studies on hysteresis loops, nearly completed, have shown that:

(i) the cyclic stress/strain curve of polycrystalline copper is closely analagous to that for single crystals,

(ii) the friction stress on dislocations is composed of a number of parts - part is equal in magnitude to the back stress and rises roughly in proportion with the root of the plastic strain. A smaller part is cycle dependent and is identified as the stress for dragging jogs on the screw dislocations which shuttle to and fro in the matrix channels. There may also be a small contribution due to dispersed point defects.

A theoretical study* has examined fatigue dislocation structures and described the processes involved in the formation of P.S.B.'s. At low strain amplitudes dipole loop patches are formed as a result of collisions and annihilations of glide dislocations. With continued cycling the patches become hard-shelled and, if the stress is high enough, the hard shell may be breached by glide dislocations giving strain bursts and re-arrangement into tilt wall elements, the P.S.B.'s. Cyclic strain is now accommodated by the movement of screw dislocations in the channels between the walls. At higher stresses the walls form into the familiar cell structure to accommodate the plastic strain.

Some earlier work on constant amplitude straining of copper single crystals had indicated that practically all of the imposed plastic strain was accommodated in P.S.B.'s, and that as the alternating level increased the volume of P.S.B.'s increased to accommodate the further strain, the saturation stress meanwhile remaining constant. Some work is now planned to study cumulative

* "Dislocation behaviour in fatigue". D. Kuhlmann-Wilsdorf and C. Laird. Mat. Sci. Eng., Vol. 27, 1977, pp. 137-156.

damage under these circumstances. One of the first questions to be examined is how the strain is accommodated when the strain level is reduced after establishing a characteristic P.S.B. structure. Do the number of P.S.B.'s decrease, or is the strain per band reduced? Such studies, covering fatigue life and deformation processes, will be made on copper single crystals and two aluminium alloys, Al-Cu and Al-Ag.

(d) Cumulative damage theory.

A phenomenological theory of cumulative damage has been developed by Hashin which defines damage in terms of the residual lifetime under an arbitrary constant amplitude stress. Thus, for specimens tested under different loading sequences but unfailed, they have suffered identical damage if they have identical residual lives under an arbitrary constant amplitude stress. In addition, an "equivalent loading postulate" is used which states that "cyclic loadings which are equivalent for one stress level are equivalent for all stress levels". This is tantamount to saying that the stress level used for the damage measurement is arbitrary, or that a damage state is definable by a single parameter. This notion of 'one parameter' damage has been thoroughly investigated by other workers and found to be unrealistic.

6.3 Visit to Lehigh University, Bethlehem, Pa., June 7, 1978.

Main purpose of visit.

To discuss environmental and load interaction effects in fatigue crack growth.

Persons contacted:

Prof. R.P. Wei, Department of Mechanical Engineering and Mechanics.
Prof. R.W. Hertzberg, Materials Research Centre.

A number of studies have been made on the mechanical and environmental factors affecting fatigue crack propagation rates and delay periods in fatigue crack growth.

(a) Crack closure

Crack closure during the unloading part of the fatigue cycle has been shown to be a real phenomenon in a Ti-6Al-4V alloy and a 2219-T851 aluminium alloy. The onset of closure as detected by electrical-potential measurements and crack-opening-displacement measurements is the same. The K-value at crack closure was found to depend upon the stress ratio R, the maximum stress

intensity of the cycle K_{max}, and specimen thickness.** The ratio of $\Delta K_{effective}$ ($=K_{max} - K_{closure}$) to ΔK applied increases with increasing R, decreases with increasing K_{max} and specimen thickness. Moreover, it has been found that strain intensification still exists at the crack tip below $K_{closure}$. Wei considers that the idea of $\Delta K_{effective}$ as a parameter for characterizing the mechanical driving force for fatigue crack growth is suspect.

(b) Delay periods in fatigue crack growth.

The delay period which occurs in fatigue crack growth after the application of an overload has been studied in a number of metals, namely 7075-T6 and 2219-T851 aluminium alloys, and Ti-6Al-4V titanium alloy. The magnitude of the delay, that is, the number of cycles for which the growth rate is retarded has been found to depend on a number of parameters.*+

(i) Delay period decreases with increase in specimen thickness (which agrees with ARL results).

(ii) For a given overload ratio (i.e. ratio of overload stress to maximum stress in the subsequent constant amplitude loading), delay increases with increasing K level.

(iii) Delay is decreased with increasing aggressiveness of the chemical environment (the order of aggressiveness was argon, air, 3.5% Na Cl).

(iv) In a corrosive environment (3.5% Na Cl) delay is dramatically increased by a factor of 40 (in Ti-6Al-4V) as the hold time at maximum load is increased from zero to 900 seconds.

** "Crack closure in 2219-T851 aluminium alloy". K.D. Unangst, T.T. Shih and R.P. Wei. Eng. Fract. Mech., Vol. 9, 1977, pp. 725-734.

* "Influences of chemical and thermal environments on delay in a Ti-6Al-4V alloy". T.T. Shih and R.P. Wei. ASTM, STP 595, 1976, pp. 113-124.

\+ "Load and environment interactions in fatigue crack growth under spectrum loading". R.P. Wei. Lehigh Univ. IFSM-78-88, Jan. 1978.

(v) Temperature affects delay. Delay is increased when the high load is applied at high temperature with subsequent fatigue at room temperature. It is reduced by intermediate heating at a high temperature following a high load excursion at room temperature, and it is lowest when fatigue loads are applied at high temperature following a high load excursion at room temperature.

It has also been observed that crack growth does not cease immediately after an overload, it may sometimes increase to be followed by a rapid decrease to a minimum (delayed retardation) and then gradually increase to its steady-state value. The delay effect appears associated with growth through the zone of material ahead of the crack tip affected by the overload. The delayed retardation is identified with crack growth through the cyclic plastic zone for the preceding fatigue loading. A residual stress intensity concept has been explored for characterizing growth after an overload but at this stage it is primitive.

(c) Interaction of environmental and mechanical effects in fatigue crack growth.

A number of studies*+ have been probing the combined influence of environmental and mechanical factors on the crack growth rate in AISI 4340 steel. Attention has been focussed on stage II in the da/dN vs ΔK curve for both sustained load and cyclic load fracture.

Experiments have determined that the embrittlement mechanism in this steel under various hydrogen gases (including water vapour) is some H-Fe reaction. But there are a number of steps which may be involved before this reaction can occur at the crack tip and any one could be rate limiting. By experimentally determining the pressure and temperature sensitivity of various reactions and of stage II cracking it has been determined that the water/metal surface reaction is the rate limiting one in a water vapour environment. In this reaction hydrogen is produced which diffuses to the crack tip (and causes embrittlement) and an oxide is formed on the surface.

* "Effect of frequency on fatigue crack growth response of AISI 4340 steel in water vapour." P.S. Pao, W. Wei and R.P. Wei. Proc. Symp. on Environment Sensitive Fracture of Engrg. Matls. AIME, 1978.

\+ "The combined influence of chemical, metallurgical and mechanical factors on environment assisted cracking". D.P. Williams, P.S. Pao and R.P. Wei. Proc. Symp. on Environment Sensitive Fracture of Engrg. Matls., AIME, 1978.

If the exposure (pressure x time) is large enough, and the crack rate (production of new surface) slow enough, the oxide can limit the reaction. Thus, there is a strong interaction between mechanical factors such as stress level and frequency which can produce a more rapid rate of production of new surface, and environmental factors.

It is Wei's opinion, as a result of these studies, that to understand (and then prevent) deleterious environmental effects, an interdisciplinary approach is required involving chemistry (surface chemistry, electrochemistry), materials science, and fracture mechanics. The alternative is an infinity of ad hoc testing.

(d) Fatigue of polymers.

A number of studies have delineated the various modes of fatigue fracture which may occur in polymeric solids. Another study has attempted to rationalise the frequency and temperature effects which are most noticeable in fatigue of polymers.

In unnotched samples, increase in test frequency always enhances hysteretic heating and premature failure. In some cases with notched samples however, increased frequency has been found to enhance fatigue life. Tests have been made on a number of polymers over a frequency range of 0.1 to 100 Hz with a variety of waveforms and over a range of temperatures. Frequency sensitivity was greatest in those polymers with a tendency for crazing. Fatigue behaviour was found to reflect a competition between strain rate and creep effects. It was also found that the frequency sensitivity was a maximum for these polymers where the β transition (chain segment jump frequency) corresponded to the test frequency at a given temperature.

6.4 Visit to University of Waterloo, Waterloo, Ontario, Canada, June 9, 1978.

Main purpose of visit.

To discuss the materials engineering approach to fatigue life prediction.

Persons contacted:

Prof. T.H. Topper, Chairman, Department of Civil Engineering.
Prof. D.J. Burns, Chairman, Department of Mechanical Engineering.

(a) Prediction of short-crack and cracked notch behaviour.

The use of the linear elastic fracture mechanics parameter K (the stress intensity) has failed when applied to small cracks in unnotched and notched samples and in the prediction of the non-propagating crack phenomenon. This problem has been solved by adding two terms to the expression for the stress intensity factor.

First, by defining ΔK as

$$\Delta K = \Delta S \sqrt{\pi(l + l_o)}$$

the use of long-crack growth data adequately predicts the growth rate of short cracks in unnotched specimens. l_o appears to be linearly related to grain size.

Second, by multiplying ΔK by the stress concentrating effect of the notch (a function of crack length), the crack behaviour from notches is adequately predicted by growth rates of long cracks in unnotched specimens. As both ΔK and K' (the notch effect) are both functions of crack length, for sharp notches a minimum occurs in crack length/stress intensity plot for sharp-notched specimens. If the minimum stress intensity is below that to propagate a crack in an unnotched specimen, a crack which has commenced to grow under a certain driving force may now experience a smaller force and growth may stop - hence a non-propagating crack.

(b) Service load histories.

Studies are being made of criteria for omitting small-load cycles in service load histories and on cycle counting and reconstitution methods.

Three omission criteria have been applied* to different published SAE service histories; sequential strain ranges, rain-flow counted strain ranges, and a stress/strain parameter simulation that accounted for mean stress effects. These are being evaluated by comparing the amount of damage reduction predicted by each criterion with actual test results. From results

* "Evaluation of small cycle omission criteria for shortening of fatigue service histories". A. Conle and T.H. Topper. Application of Computers in Fatigue Conference, SEECO, 1978.

to date the actual damage differences are much greater than those predicted for all criteria but the sequential strain range statistic appears to be the most appropriate of the three.

Load sequence reconstitution methods are being studied by tests on unnotched mild steel specimens. Tests are being made under SAE random load histories and under reconstituted histories using 2, 3 and 4d Markov reconstitution methods.

(c) Bi-axial fatigue.

Tests are being made on tubular specimens with axial and internal or external pressure loadings using electrohydraulic servo control. The aim is to determine the deformation characteristics in the +, + quadrant and relate these to fatigue life. Preliminary results indicate that fatigue softening is somewhat different under bi-axial conditions and the Von Mises criterion is inappropriate. In addition, saturation occurs much faster and is more stable under bi-axial loading.

The disadvantage of the bi-axial system mentioned above is the messy arrangement of using oil pressure loadings, but its great advantages are that loadings in more than one quadrant can be examined and both stress and strain can be measured and controlled in the plastic region. Topper described two other systems in use elsewhere. One uses similar specimens but has both axial and torsion loading. The advantage is that no pressurization is required, but the loading is limited to one quadrant. The other system uses a cruciform specimen, dished at the centre and loaded axially in two directions at right angles. The advantages are no oil, good visibility and stressing in all quadrants, but the disadvantage is that strain gauges must be used on the test section to determine strains, and stresses in the plastic region are unknown. This system is therefore inadequate for cyclic stress/strain control.

(d) Extension of basic cyclic stress/strain concepts.

It has been established that for metals obeying the Masing hypothesis (which states that the shape of any stress/strain excursion is described by the cyclic stress/strain curve) the stress/strain behaviour under any loading sequence is predictable. A theoretical analysis and experimental program* have shown that

* "Structural cyclic deformation response modelling". D.P. Williams, N.C. Lind, A. Conle, T.H. Topper and B.N. Leis. Mechanics in Engineering, Univ. Waterloo Press, 1976.

Masing behaviour in the metal results in similar behaviour in structural elements, and under these conditions the deformation response of <u>structural elements</u> is predictable under any loading sequence.

(e) Miscellaneous studies in Department of Mechanical Engineering.

(i) Ships transporting LP gas contain tanks which rest on balsa wood blocks. With ship motion, fatigue of these blocks has occurred and fatigue tests have been made to gather design data.

(ii) Prediction of low-cycle high-temperature fatigue failure. Tests are being made on a number of metals and an attempt is being made to predict the behaviour using a non-linear summation of creep and fatigue.

(iii) High pressure cutting of materials is being developed. Water jets from pressures of 60,000 to 100,000 p.s.i. have been used to develop a commercial machine with numerical control for cutting shoe materials. A machine using a pulse-jet and similar pressures is being developed for cutting concrete paving.

(iv) A solution of the stress intensity of cracks with unusual geometries has been developed. This is being validated by (a) applying the solutions to shapes for which the stress intensity factor is known, and (b) fatiguing PMMA with an artificially-made internal defect.

(v) The effect of a water environment on the fatigue life of a steel is being investigated under a temperature of 500^{o}C and a pressure of 1000 p.s.i. - under these conditions the water is not boiling.

7. <u>CONCLUSION</u>

The discussions held with Mr. C.L. Harmsworth, the manager of the joint ARL/AFML project on corrosion fatigue in D6AC steel joints, were most productive, held in a cooperative spirit, were believed to be indispensable to the achievement of a high-quality final report, and adequately safe-guarded the contributions of ARL.

Invaluable updating was achieved by attending a Symposium on Fatigue Mechanisms and making other technical visits. Some discussions held at AFML could well develop into a cooperative program on low-cycle fatigue investigations of aircraft engines.

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16. ABSTRACT:

In May/June 1978, the author visited the U.S. Air Force Materials Laboratory to arrange the joint final report for the "US/Australia Collaborative Research Project on Corrosion Fatigue in D6AC Steel Joints". This report details those discussions and other discussions on the fatigue of materials held during associated technical visits. In addition, a brief report is given of the proceedings of a Symposium on Fatigue Mechanisms also attended.

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